# DEVELOPMENT OF LOW DENSITY TITANIUM ALLOYS FOR STRUCTURAL APPLICATIONS

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## ABSTRACT

In this report the results of a program designed to reduce the density of titanium by adding magnesium are presented.  Because these two elements are immiscible under conventional ingot metallurgy techniques, two specialized powder metallurgy methods namely, mechanical alloying (MA) and physical vapor deposition (PVD) were implemented.

The mechanical alloying experiments were done both at the University of Idaho and at the Defense Research Agency in UK.  Since titanium is reactive with interstitial elements, a secondary goal of this research was to correlate solubility extensions with interstitial contamination content, especially oxygen and nitrogen.  MA was carried out in SPEX 8000 shaker mils and different milling containers were utilized to control the level of contamination.  Results showed that solubilities of Mg in Ti were obtained up to 28 at.% (16.4 wt. %)  Mg in Ti for Ti- 39.6 at. % (25 wt. %) Mg alloys, which greatly exceed those obtained under equilibrium conditions.  This reflects a density reduction of approximately 26 %.  Contamination of oxygen and nitrogen seemed to increase the solubility of magnesium in titanium in some cases; however, we were not able to make a clear correlation between contamination levels with solubilities.

Work at the DRA has emphasized optimization of present PVD equipment, specifically composition and temperature control.  Preliminary PVD data has shown Ti-Mg deposits have successfully been made up to 2 mm thick and that solubility extensions were achieved.

The potential for density reduction of titanium by alloying with magnesium has been demonstrated; however, this work has only scratched the surface of the development of such low density alloys.  Much research is needed before such alloys could be implemented into industry.  Further funding is required in order to optimize the MA/PVD processes including contamination control, determination of optimal alloy compositions, microstructure development, and mechanical property determination.

# 1. INTRODUCTION

Titanium alloys offer very attractive combinations of high strength, high toughness, creep resistance, elevated temperature capability and environmental stability. Although much effort has been devoted to increasing the strength of titanium alloys by conventional ingot metallurgy routes, it has been recognized that a density reduction is 3-5 times more effective in reducing structural weight of aerospace vehicles than increases in strength or modulus. However, the options for reducing density by conventional alloying are very few (Table 1), [1,2].

An alternative approach is to use rapid solidification (RS) or other advanced synthesis techniques to produce a supersaturated metastable titanium solid solution alloy containing light elements. Magnesium is particularly attractive for this purpose because it has a low density, the same crystal structure as titanium and the electronegativity criterion suggests that compound formation is not likely. The valency of magnesium (2) is different from that of titanium (4) and this can limit the extent of solid solubility of magnesium in titanium. Further, because the boiling point of magnesium is below the melting temperature of titanium, magnesium is impossible to be added to titanium by conventional ingot metallurgy methods.

This program utilized two advanced synthesis techniques -- mechanical alloying (MA) and physical vapor deposition (PVD) to synthesize and evaluate low density Ti-Mg alloys. The MA work has been done at the University of Idaho while the PVD work was accomplished as a sub-contract at the Defense Research Agency (DRA) at Farnborough, UK.

Mechanical alloying is a solid-state powder processing technique involving repeated welding, fracturing, and rewelding of powder particles in a dry, high energy ball charge (Fig. 1) and has been shown to be capable of producing supersaturated solid solutions in a number of alloy systems.

In preliminary work limited success was achieved in alloying titanium with magnesium using MA methods [3-5]. At the University of Idaho, it was demonstrated that by changing the processing conditions the solid solubility limits can be increased. For example, when the two elemental powders were blended together and MA'd a maximum solid solubility of only 1.4 at.% (0.7 wt.%) Mg in Ti was achieved. On the other hand, when the two powders were pre-milled for 2h separately and then blended together and MA'd, a higher value of 3.6 at.% (1.9 wt.%) was achieved [6]. In investigations on other titanium-base alloy systems, the milling atmosphere, ball to powder ratio, the quantity of charge, and other variables have also been shown to affect the maximum solid solubility achieved [3]. In the physical vapor deposition (PVD) method, heating (for example by electron beam or induction methods) is used to melt and evaporate metals or alloys, and the vapor is condensed onto a heated collector plate which is held at a constant temperature throughout the deposition (200°C or 300°C) (Fig. 2). The evaporation takes place within a vacuum chamber, typically held at a pressure of about $2 \times 10^{-6}$ torr.

In previous work, the PVD method was used to produce deposits of an Al-Fe-Cr alloy up to 50 mm thick and in slabs up to 1000 mm x 500 mm in size; clearly demonstrating that this is not just a process which is a laboratory curiosity. In titanium-magnesium alloys previous work done at the DRA and characterized by x-ray diffraction

indicated that the alloys were generally complete solid solutions of titanium and magnesium up to at least 28 wt. % Mg [7].

## 2. EXPERIMENTAL PROCEDURES

### 2.1 MECHANICAL ALLOYING

Mechanical alloying was done for the major purpose of increasing the solubility of magnesium in titanium to produce low-density titanium alloys. A secondary goal was to identify a possible correlation between the solubility level achieved and the interstitial contamination introduced during milling.

### 2.1.1 MECHANICAL ALLOYING: University of Idaho

Mechanical alloying was carried out in a high-energy SPEX 8000 shaker mill, with the process consisting of loading the powder mix and a grinding medium ( 52100 hardened steel balls) in a container under a protective argon atmosphere (to avoid/minimize the pickup of interstitial contamination, particularly oxygen and nitrogen, during the milling operation), followed by milling. Before starting, the milling media and containers were cleaned thoroughly with methanol. The powders were loaded in one of two protected environments: a Plas Labs clamshell type glove box and a Labconco controlled atmosphere glove box. The former, believed to be inefficient in isolating contamination, was used at the outset of the program until the Labconco instrument became operational. Since milling was carried out in the laboratory atmosphere, keeping the powder free of contaminants during milling was difficult.

## MILLING CONTAINERS

Four different milling containers were used in an attempt to control/minimize the contamination. The first, (a) designated "SPEX" throughout this report, was the standard SPEX design consisting of three parts: the top, bottom (both made of hardened steel with a small 'O'-ring), and the clamping flange made of aluminum. The second vial (b), designated "MSPEX", was a standard SPEX container modified with a larger 'O'-ring groove and larger, softer 'O'-ring. The third (c), designated "UI", was a novel University of Idaho design implementing a flat gasket, complete with a steel clamping flange. The fourth design (d), "UWA", was recently obtained form the University of Western Australia. This container is characterized by an 'O'-ring seal and a modified steel clamping device.


## EXPERIMENTS

Seven experiments were done, generally implementing the first three milling containers (as the last one was only recently acquired) and varying several milling parameters: ball to powder ratio (BPR), milling time, tightening condition, and in some cases, milling container. Details of these experiments are listed in Table II.


## 2.1.2  MECHANICAL ALLOYING:  Defense Research Agency

Only one experiment involving mechanical alloying was done at the DRA. This was done to reconfirm the results obtained from experiments 1 and 2 done at the University of Idaho. In this experiment, titanium-magnesium powders with 9 to 24 wt.% (16.31 to 38.4 at.%) magnesium were milled in a SPEX 8000 shaker mill. Further, a flat neoprene gasket was used instead of a conventional "O"- ring in this case. However, the mill was put in a

glove box to minimize contamination. The chemical analysis for these powders is not yet available.

## 2.2 PHYSICAL VAPOR DEPOSITION

At the Defense Research Agency, a dedicated PVD rig was commissioned that used an electron beam (EB) melted titanium rod source and a thermal evaporation source for the sublimation of magnesium additions. Initial trials depositing pure titanium or magnesium separately were conducted to assess the relationship between EB power/magnesium evaporation temperature and deposition rate.

## 2.3 CHARACTERIZATION

X-ray Diffraction (XRD) was the major technique used to characterize the mechanically alloyed powder. XRD was done with a SIEMENS D5000 diffractometer using Cu $K_\alpha$ radiation of wavelength 0.15406 nm and at 40 kV and 30 mA settings. Lattice parameters were calculated using a Quickbasic program based on Cohen's method. Cohen proposed that a method of plotting the parameters vs. $\sin^2\theta$ be used to obtain a series of equations which could be solved simultaneously for more precise lattice parameters [8]. After obtaining the lattice parameters, the solid solubility was calculated for all experiments based on Vegard's law, which states that the lattice parameters of a solid solution vary linearly with the atomic percent of solute present [8]. Solid solutions in hexagonal close-packed metals such as titanium and magnesium, are known to deviate from linearity and therefore Vegard's law was used as a first approximation in this work. Oxygen and nitrogen levels were determined by wet chemistry at no cost to the program by Crucible Research of Pittsburgh, Pennsylvania.

## 3. RESULTS

### 3.1.1 MECHANICAL ALLOYING: University of Idaho

Experiments 1 and 2 were done first to see how increasing the nominal solute content correlated to the resulting solid solubility extension and interstitial contamination after milling. The resulting lattice parameters, solid solubilities based on these lattice parameters, and the chemical analysis are presented in Table III. For convenience, the data obtained on milling pure Ti under similar conditions are also included. From the results of this experiment, it is noticed that solubility extensions were obtained far exceeding equilibrium values. For example, in Ti - 39.6 at%. Mg, the solubility of Mg in Ti exceeded 27 at. % (16 wt. %). In addition, two trends were identified: (i) solid solubility increased with increasing solute concentration and (ii) oxygen and nitrogen concentration also increased with increasing solute concentration. The results for the "c" parameter reflect this more systematically than do those for the "a" parameter. The data showing the trend between wt.% oxygen and nitrogen versus wt.% actual Mg are presented in Fig. 3, while the correlation between the solubility of magnesium in titanium based on the "c" parameter versus wt.% $O_2$ and $N_2$ are shown in Figs. 4 and 5, respectively.

To verify the results of the previous experiment, experiment 2 was conducted with only half as much starting powder (5g). The data collected for this series of experiments are presented in Table IV. These data confirm the same trends as observed in the previous experiment. However, the trend on the solid solubility of Mg in Ti is much more systematic in this series of experiments. Both the "a" and "c" parameters indicate increasing solid solubility of Mg in Ti with increasing nominal Mg content in the starting powder, although the extensions of solubility are slightly lower than in the previous

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experiment. The reason for this remains unclear and will require further investigation. Again, under similar milling conditions as the first experiment, chemical analysis showed increasing contamination with initial solute content (Fig. 6). However, the plots of solid solubility vs. contamination data for both oxygen and nitrogen do not follow the linear variation observed for experiment 1. The data are much more scattered for the solubility based on the "a" parameter (Figs. 7 and 8) than that plotted against the "c" parameter (Figs. 9 and 10).

Since it was verified in the previous two experiments that the amount of contamination increased as solute concentration increased, it was decided that two different compositions would be milled under different conditions, and their contamination levels compared. By milling two different compositions and comparing their contamination and solubility levels, we would expect the alloy with the higher concentration of solute to have more contamination and higher solubility levels than the alloy of lesser solute content. Ti-15 wt. % Mg and Ti-9 wt. % Mg (experiments 3 and 4, respectively) were chosen. Variations for these experiments include: milling containers, milling times, and container tightening conditions.

The data collected from experiment 3 (Table V and Figs. 11 and 12) exhibits so much scatter that no correlation between solubility and amounts of oxygen and nitrogen can be made. We believed prior to these experiments that increasing contamination would limit solubility extension. The data is even more scattered for the Ti-9 wt. % Mg in experiment 4 (Table VI and Figs. 13 and 14). It is noticed from Table VI, that some trials in experiment 4 did not even reach minimal solubility extensions. This is probably due to the short milling times. However, this does not explain the relatively large solubility levels

reported for the SPEX vial in experiment 3 (Table V) where solubilities reached 32 wt. % Mg in Ti. These are truly puzzling and will require further study.

Because of inconclusiveness of the previous experiments, a new set of experiments were conducted in order to establish our premise that increasing contamination decreased solubility. Ti-15 wt.% Mg powder was milled for hourly increments in a loosely tightened SPEX milling container. In this experiment we deliberately introduced contamination, and then calculated the solubility extensions obtained. Both oxygen and nitrogen levels in the powder increased with increasing milling time and the results are presented in Table VII. Except for one irregularity in the values corresponding to hour 6, the contamination increased fairly consistently. The solubility data is somewhat scattered and presents difficulty when attempting to correlate contamination with solubility (Fig. 15 and 16). The same kind of experiments were done with Ti-9 wt. % Mg. Experiment 6 was conducted by removing samples from the loosely sealed milling container from 1 to 6 hours. While we were able to deliberately introduce contamination into the container, we were not able to achieve any solubility of Mg in Ti even up to 6 hours of milling for this composition and therefore these results are not included in this report. Based on our results from experiment 4 where solubilities were obtained in powders milled up to six hours, we pre-milled Ti-9 wt.% Mg powder for seven hours before removing powder samples for study constituting experiment 7. These results are tabulated in Table VIII. Again, when the solubility data is plotted (Figs. 17 and 18), no direct correlation is apparent between contamination and solid solubility.

### 3.1.2 MECHANICAL ALLOYING: Defense Research Agency

The data from this experiment, conducted and characterized by x-ray diffraction at the DRA, are presented in Table IX. The solid solubility of Mg in Ti was calculated by us here at the UI by the same method previously described. The trend of increasing solubility of magnesium in titanium with increasing solute content was reconfirmed. The chemical analysis of these powders is not yet available.

### 3.2 PHYSICAL VAPOR DEPOSITION

To date, efforts have primarily focused on installing and modifying the vapor deposition apparatus. In the current apparatus, a deposition rate of ~ 1 mm/h was obtained giving a maximum deposit thickness of ~ 2 mm, although alterations are currently being made to significantly increase this. Compositional control was difficult to achieve in initial deposits of Ti-Mg as the evaporation rate of the magnesium depends heavily on the extent of the exposed surface area of the Mg feedstock. The temperature of the collector plate was also unstable during trial runs and this seemed to have a considerable effect on the composition/properties of the material produced. This problem was solved using a series of thermocouples and an electronic controller. The stability of both the collector and the Mg temperatures can now be accurately controlled throughout the runs. Since these problems have now been fully addressed, it should be possible to exactly tailor the composition, and therefore, the properties of the deposits. There is some evidence that these alloys will respond to heat treatment as previously observed, giving dramatic increases in hardness/strength. The next stage of the project is to produce a controlled series of alloys and to tailor the properties of these through heat treatment/hot pressing.

# 5. CONCLUSIONS

The preliminary work reported here has indicated the potential for the development of low density titanium using 5 to 30 wt. % (9.4 to 39.6 at. %) magnesium additions. Solubility extensions during MA resulted in all cases with a maximum solubility of 28 at. % (16.4 wt. %) for Ti- 39.6 at. % (25 wt. %) Mg. When the lattice parameters of the characterized powder are plotted vs. at. % Mg (Figs. 19 and 20), results from MA and PVD processing reflect consistent solubility extensions. Contamination has been difficult to control and its effect on solubility extensions requires further study. It has yet to be determined whether or no contamination has an effect on solubility extensions of Mg in Ti.

We anticipate that solubilities can be extended further only after optimizing processing conditions and/or alloy composition, and by controlling interstitial contamination. Additionally, more work is needed to optimize the microstructure and to determine mechanical properties before these alloys could be implemented into industry. Discontinuing funding for this program will prove detrimental to the development of the information base required before these potentially cost effective alloys could be put into use commercially.

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6. Zhou, E., C. Suryanarayana, and F. H. Froes, *Mater. Letters*, 1995, **23**, 27-31.
7. Ward-Close, C.M., P.G. Partridge, P. Holdway and A.W. Bowen, "An X-ray Diffraction Study of Vapor-Quenched Titanium Magnesium Alloys", in Proceedings of the 7th World Conference on Titanium, eds. F.H. Froes and I.L. Caplan, TMS, Warrendale, PA, 1992, 659-666.
8. Cullity, B.D., Elements of X-ray Diffraction, 2nd ed., Addison-Wesley Pub. Co., 1978.

## FIGURE CAPTIONS

# LIST OF TABLES

Fig. 2 Schematic of Physical Vapor Deposition Apparatus.
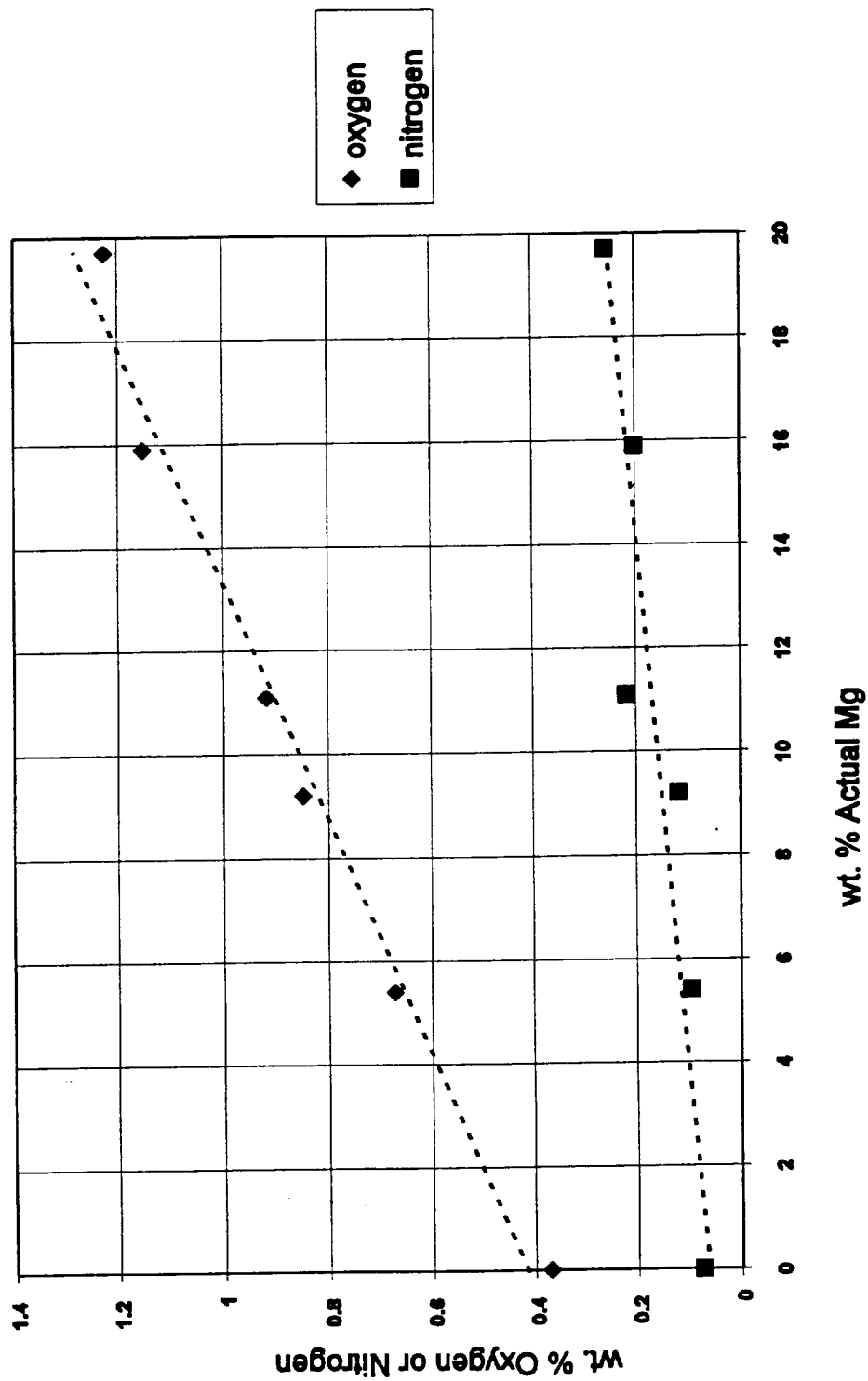


Fig. 1. Schematic of Mechanical Alloying process.

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Fig. 3. Weight percent oxygen and nitrogen versus weight percent actual magnesium, experiment 1.

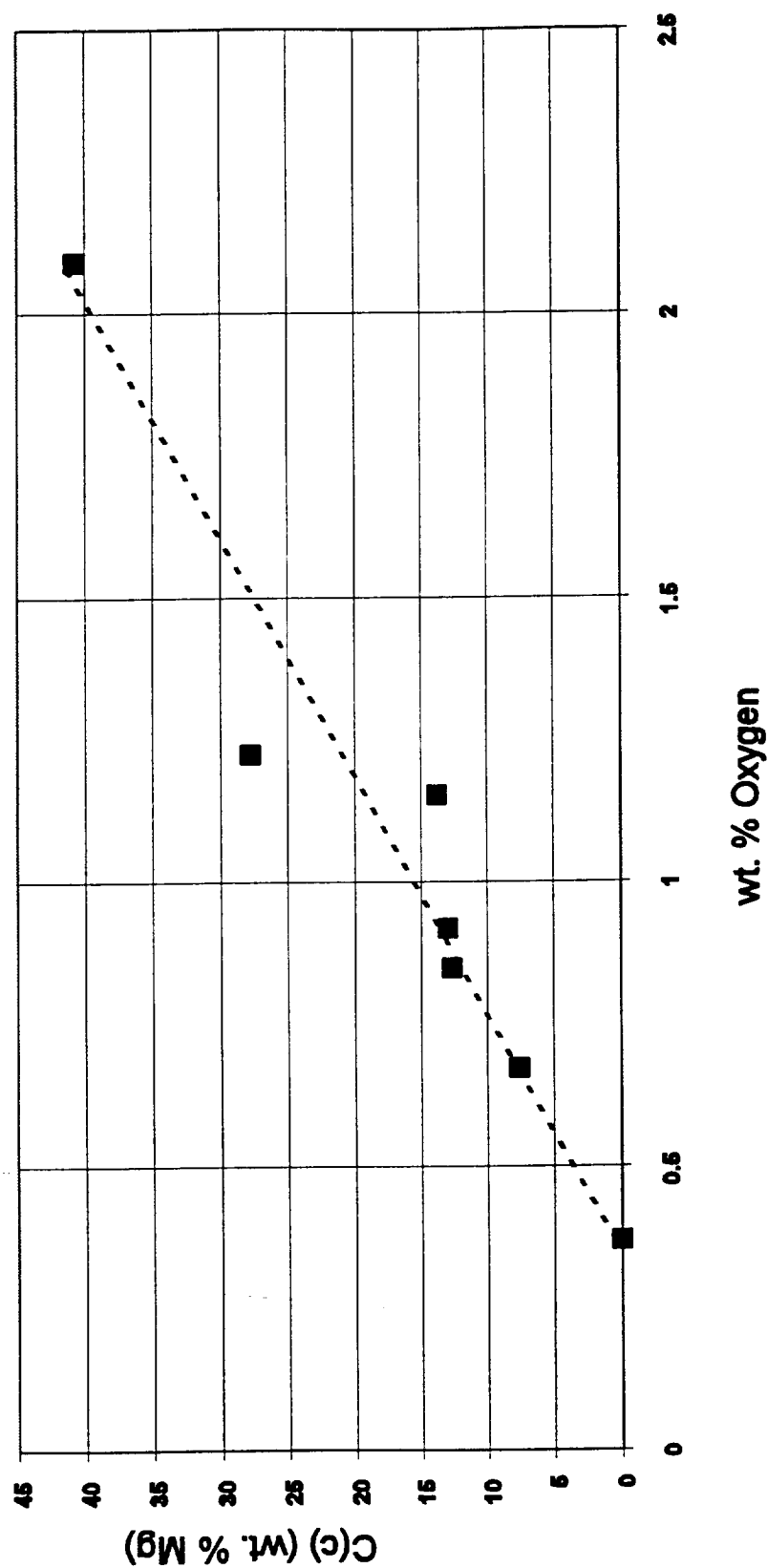## Solid Solubility vs. Oxygen Contamination
### Experiment 1 (including pure Ti)

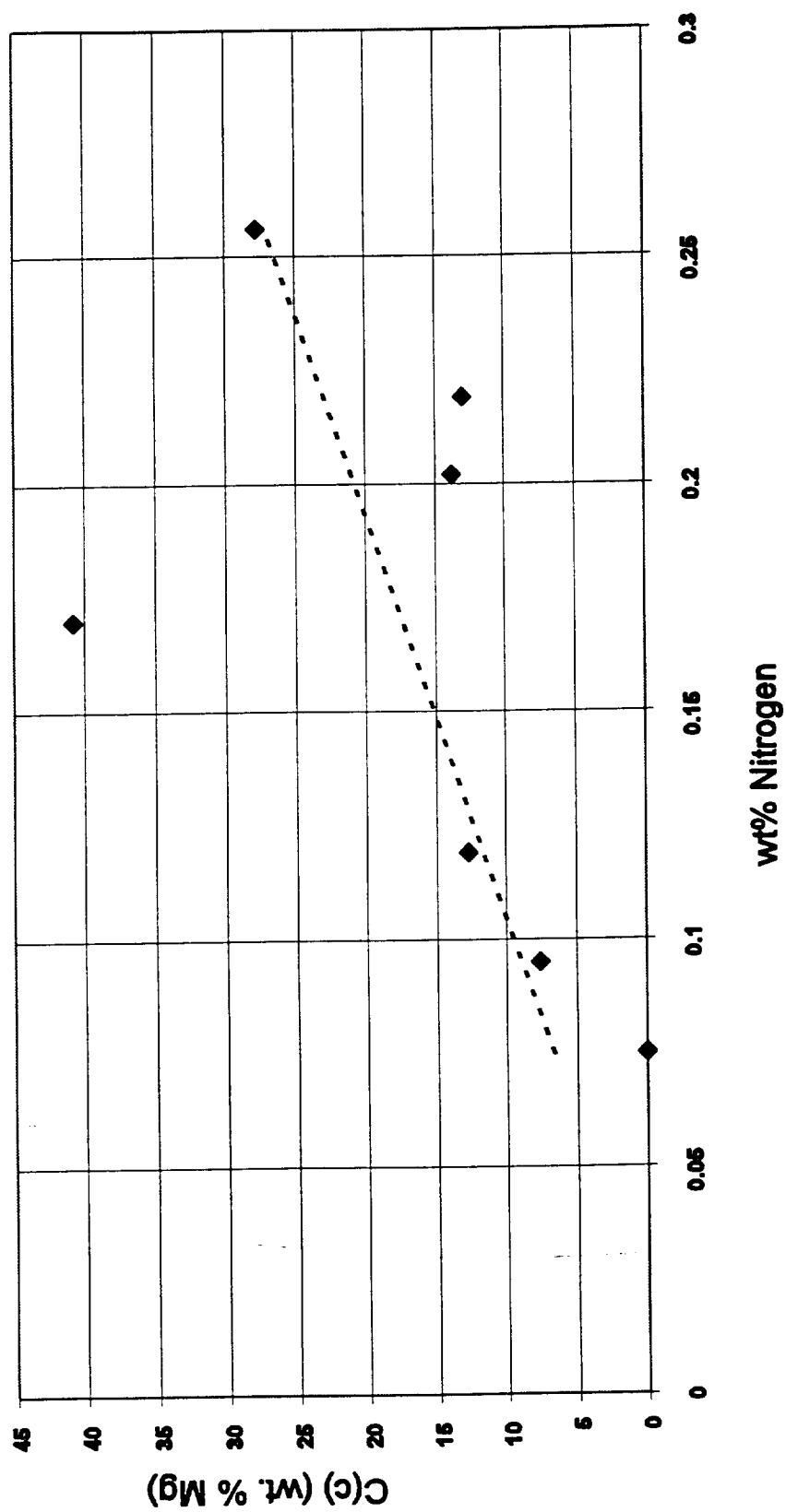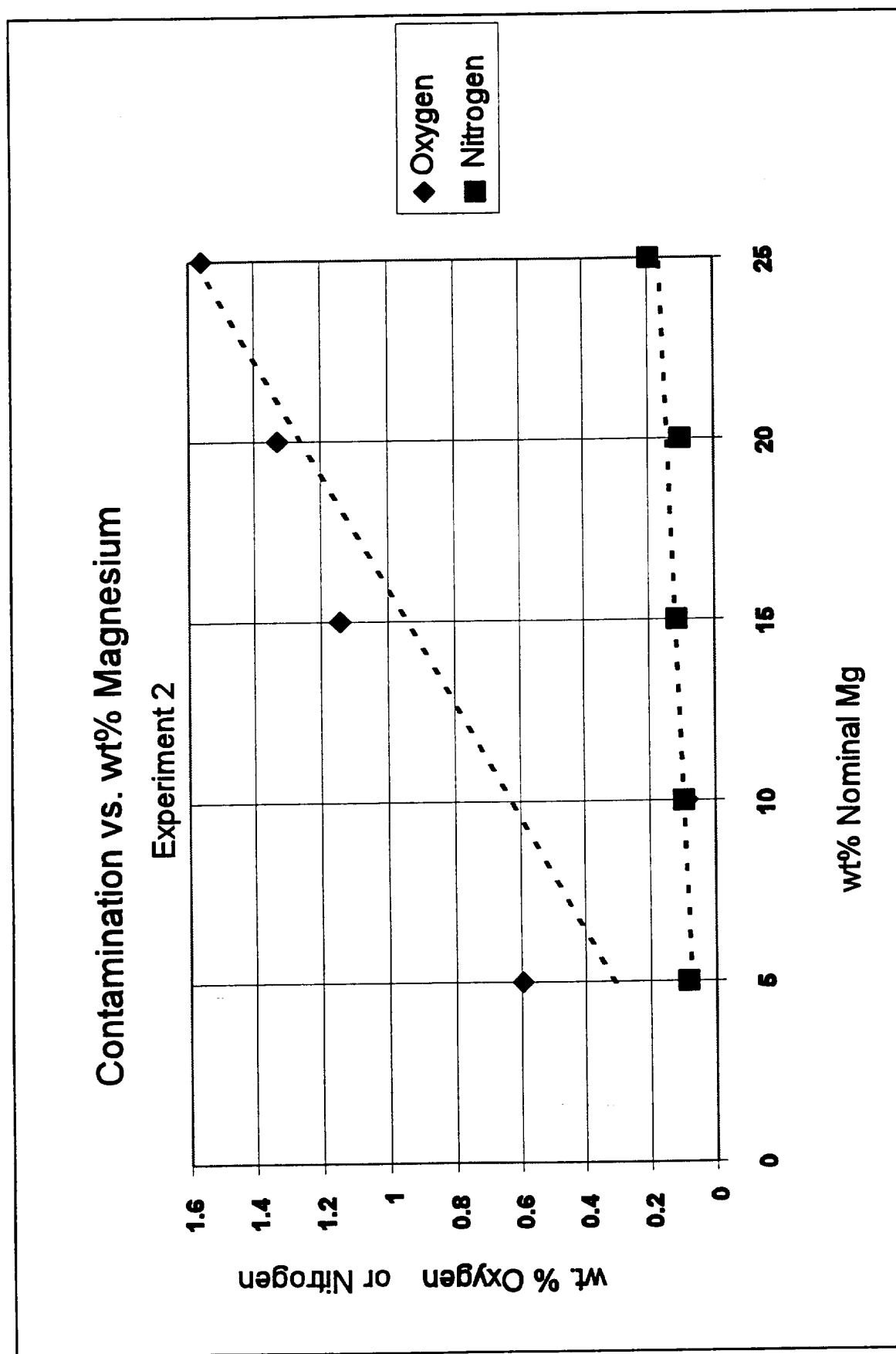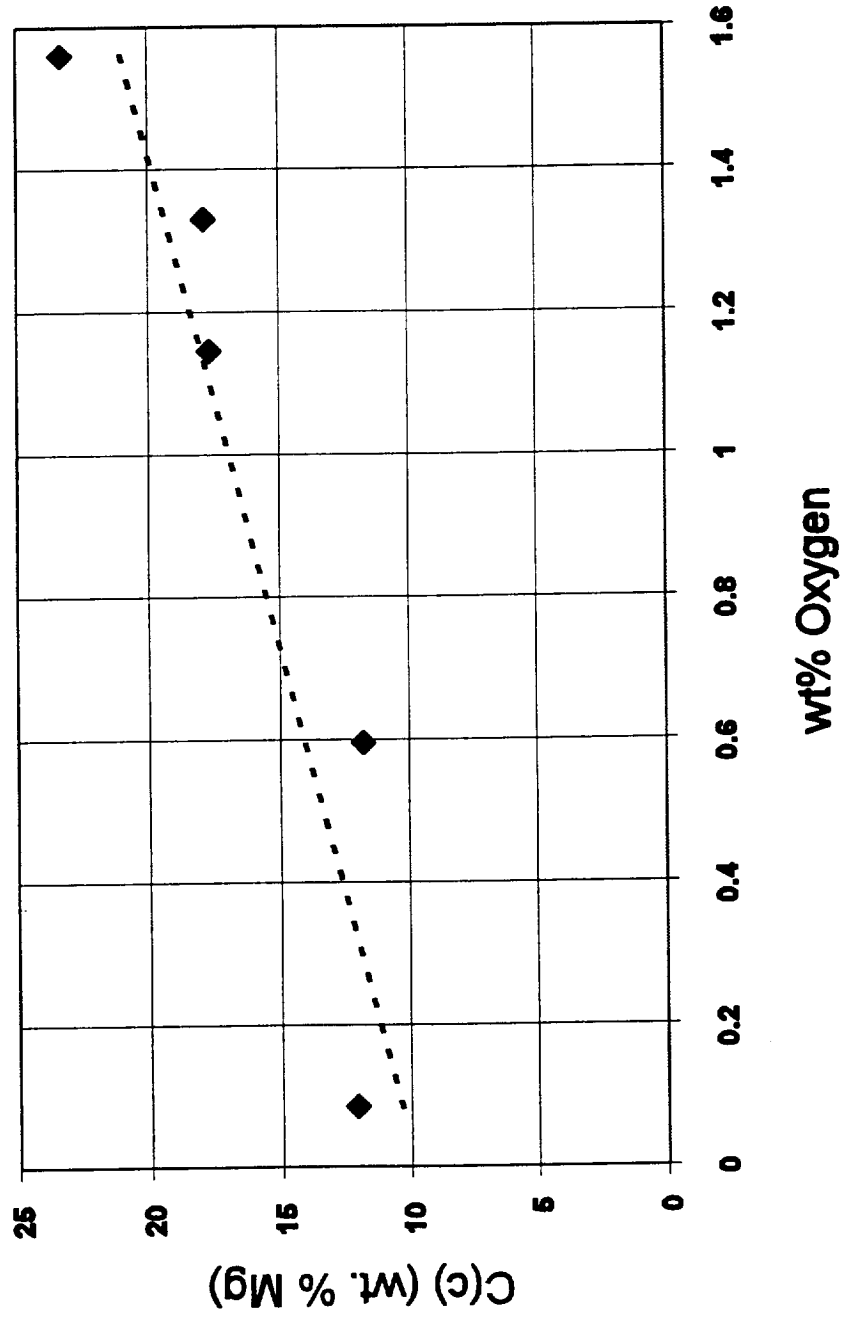Fig. 4. Solid solubility versus oxygen contamination, experiment 1.

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Fig. 5. Solid solubility versus nitrogen contamination, experiment 1.

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Fig. 6. Contaminaiton versus weight percent Mg, experiment 2.

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Fig. 7. Solid solubility based on "a" parameter versus oxygen contamination, experiment 2.

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Fig. 8. Solid solubility based on "a" parameter versus nitrogen contamination, experiment 2.

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**Fig. 9.** Solid solubility based on "c" parameter versus oxygen contamination, experiment 2.

23
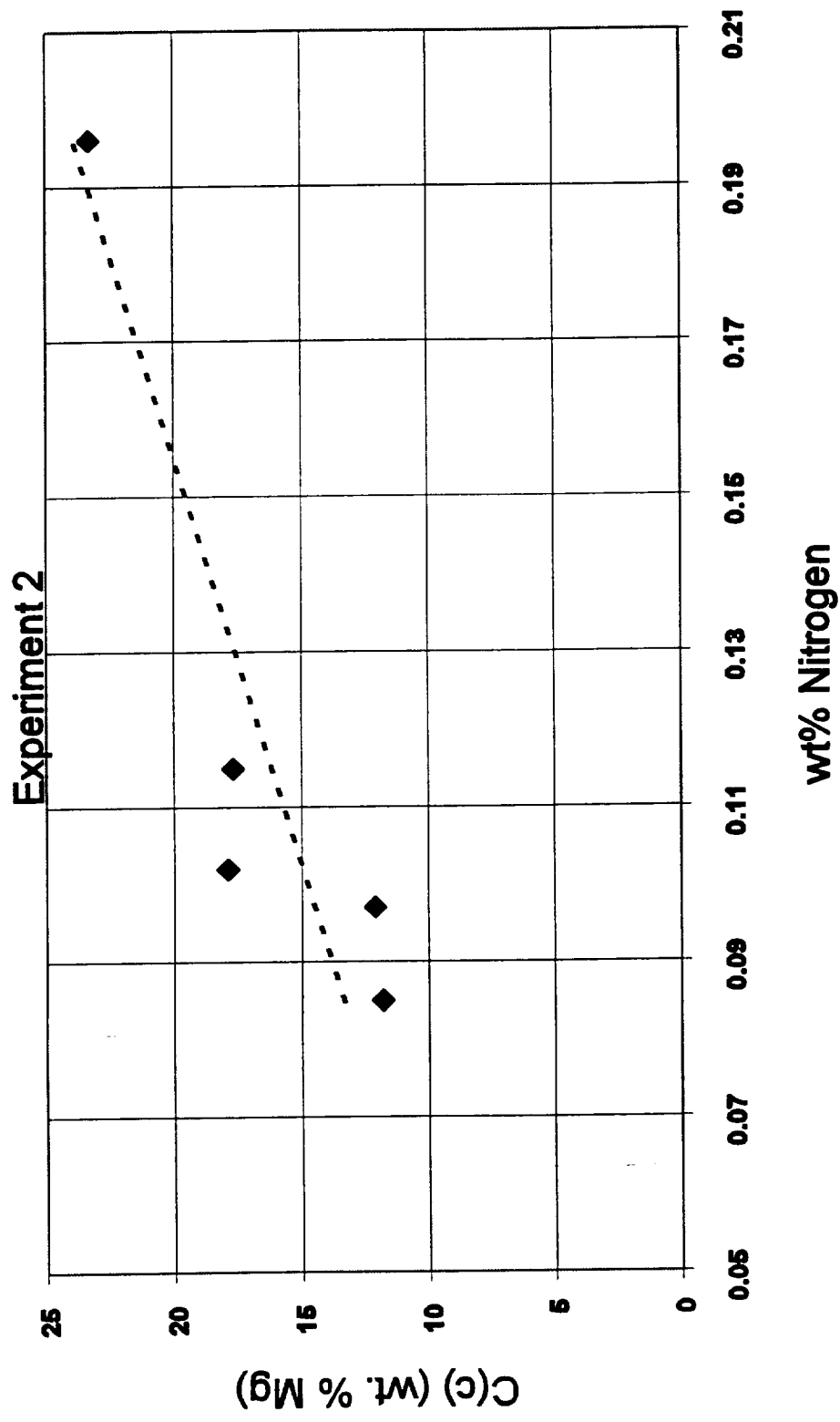
Fig. 10. Solid solubility based on "c" parameter versus nitrogen contamination, experiment 2.

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Fig. 11. Solubilites versus weight percent oxygen, experiment 3.
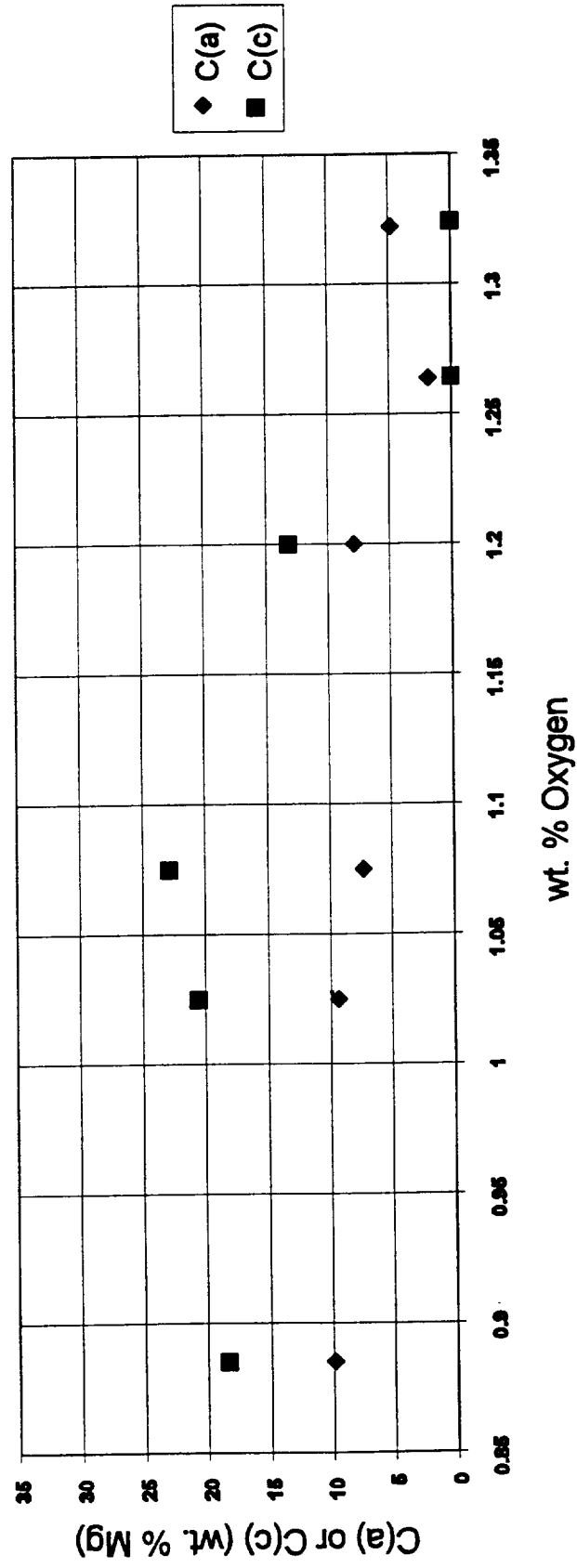
25
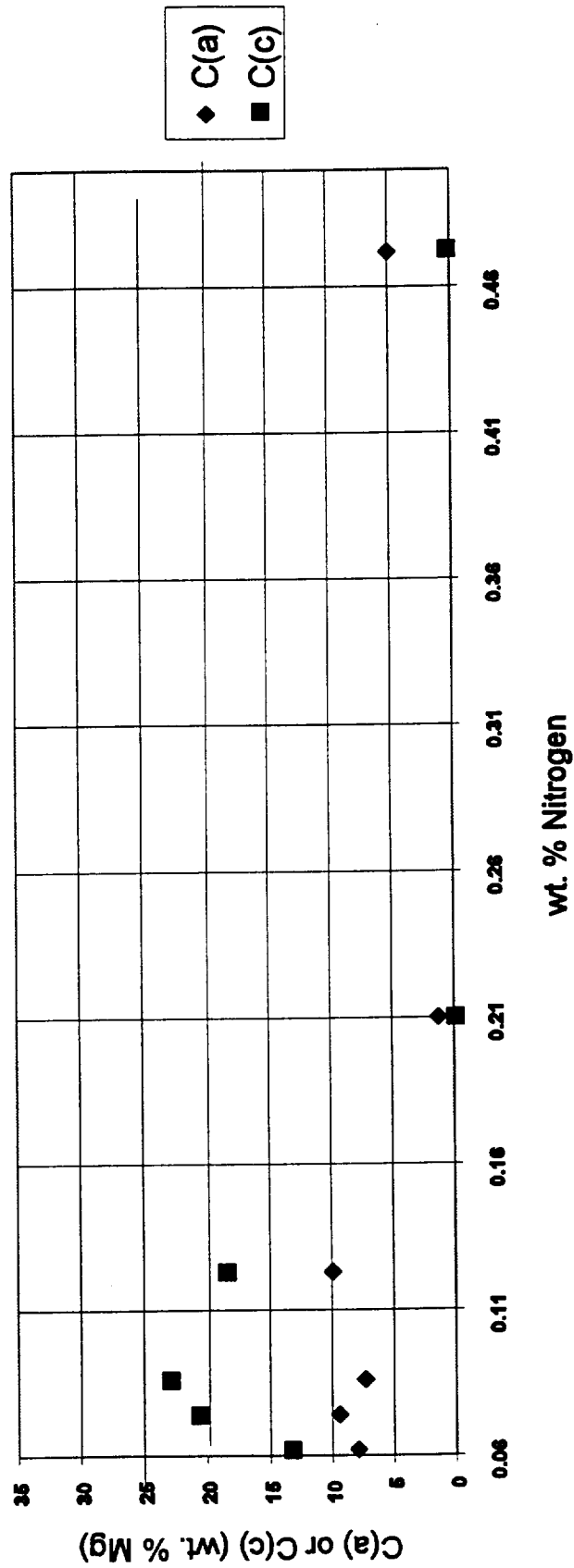
Fig. 12. Solubilites versus weight percent nitrogen, experiment 3.
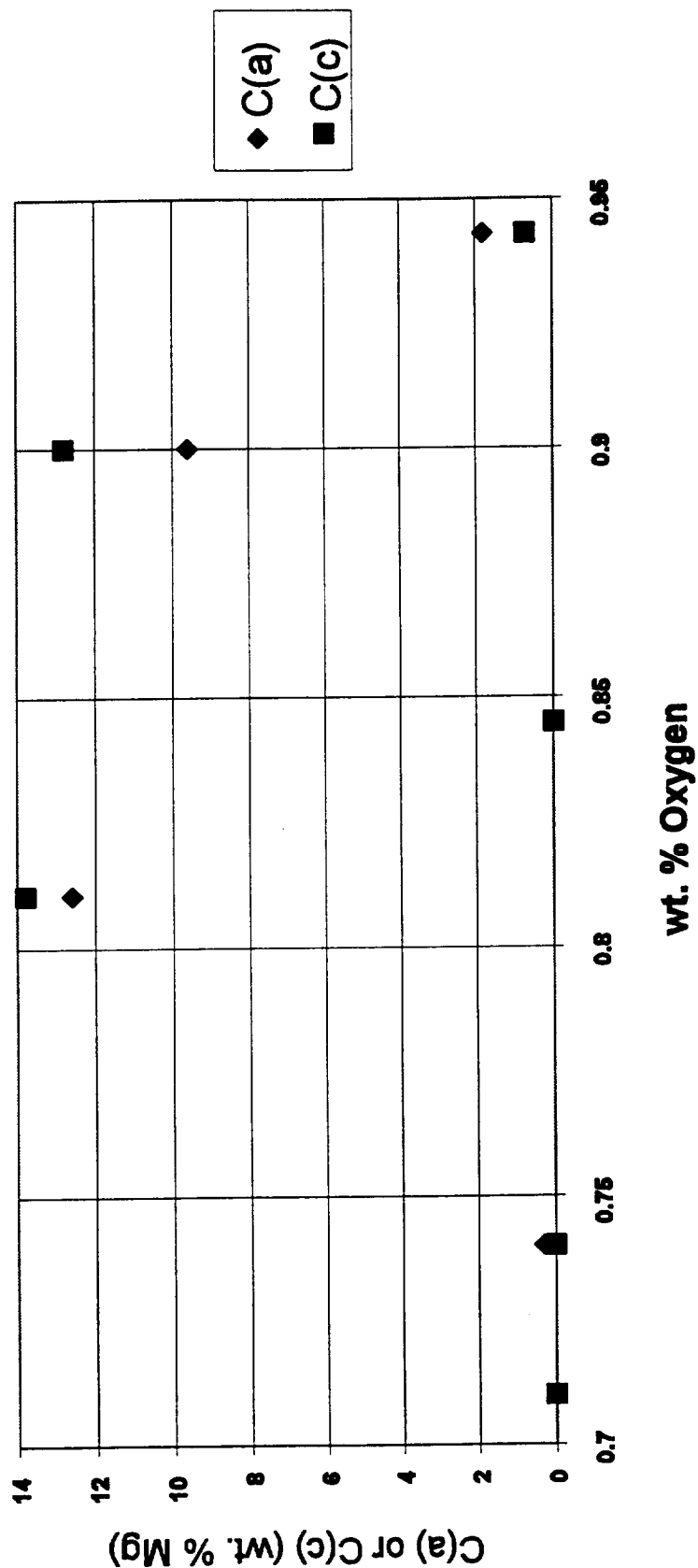
Fig. 13.    Solubilities versus weight percent oxygen, experiment 4.

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Fig. 14. Solubilities versus weight percent nitrogen. experiment 4.

Fig. 15. Solubilities versus weight percent oxygen, experiment 5.

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Fig. 16. Solubilities versus weight percent nitrogen, experiment 5.

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Fig. 17. Solubilities versus weight percent oxygen, experiment 7.

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Fig. 18. Solubilities versus weight percent nitrogen, experiment 7.

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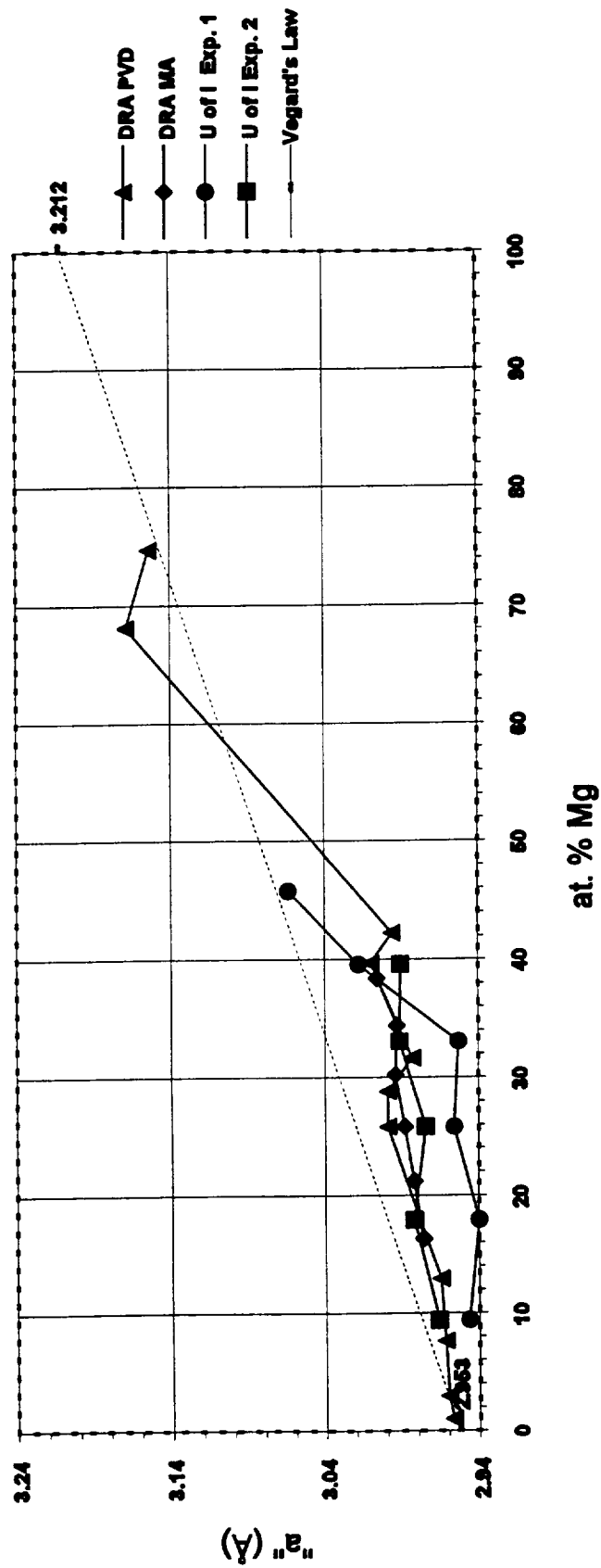
Fig. 19. "a" parameters versus atomic percent magnesium for various experiments.

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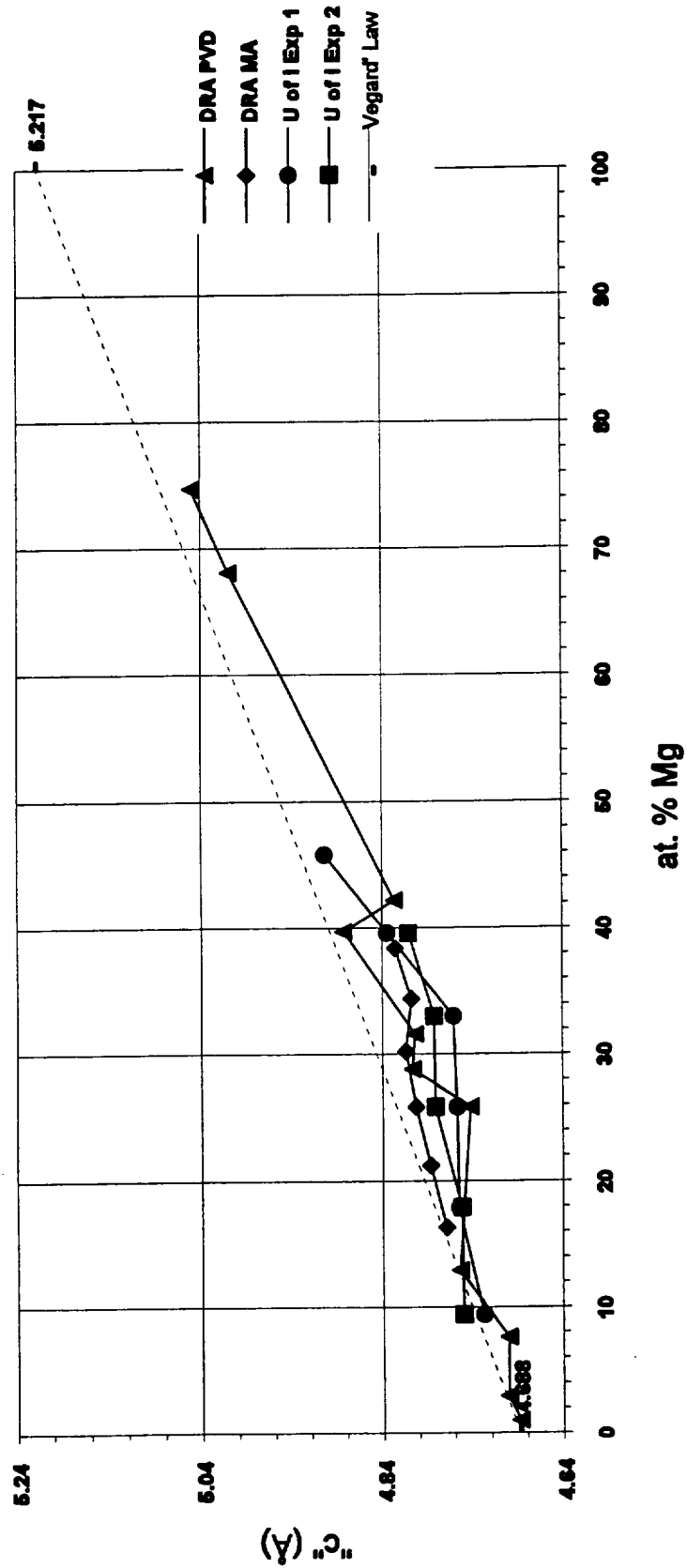
Fig. 20. "c" parameters versus atomic percent magnesium for various experiments.

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Table I.  Properties of elements which can reduce the density of titanium [1,2].

| Element | Density (g/cm³) | Melting Point (°C) | Boiling Point (°C) | Tendency to Form Compounds | Solid Solubility in α-Ti at 20°C (at. %) |
|---------|-----------------|--------------------|--------------------|----------------------------|------------------------------------------|
| Li | 0.53 | 179 | 1317 | no compound | -- |
| Ca | 1.54 | 851 | 1482 | no compound | -- |
| Mg | 1.74 | 651 | 1090 | no compound | < 0.2 |
| Be | 1.85 | 1284 | 2970 | Forms intermetallics | -- |
| C | 1.88 | 3550 | 4827 | Forms intermetallics | < 0.5 |
| Ai | 2.33 | 1410 | 2355 | Forms intermetallics | < 0.5 |
| B | 2.34 | 2079 | 2550 | Forms intermetallics | -- |
| Al | 2.70 | 660 | 2467 | Forms intermetallics | 11 |
| Sc | 2.99 | 1539 | 2831 | no compound | < 3 |
| Ti | 4.54 | 1668 | 3260 | --- | -- |

Table II. Summary of MA experiments done at University of Idaho.

| Expt. # | Composition | Milling Container | Milling Time (h) | Charge Weight (g) | Tightening Conditions | BPR |
|---|---|---|---|---|---|---|
| 1 | Ti-X wt. % Mg X = 5,10,15,20,25 | SPEX | 20 | 10 | Wrench | 10:1 |
| 2 | Ti-X wt. % Mg X = 5,10,15,20,25 | SPEX | 20 | 5 | Wrench | 10:1 |
| 3 | Ti - 15 wt. % Mg | All 4 | 20 | 10 | Wrench, Hand | 10:1 |
| 4 | Ti - 9 wt. % Mg | All4 | 6 | 10 | Wrench, Hand | 10:1 |
| 5 | Ti - 15 wt. % Mg | SPEX | From 1-7 | 10 | Hand | 10:1 |
| 6 | Ti - 9 wt. % Mg | SPEX | From 1-6 | 10 | Hand | 10:1 |
| 7 | Ti - 9 wt. %Mg | SPEX | From 8-16 | 10 | Hand | 10:1 |

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Table III. Results from experiment 1.

| Mg Content | | Lattice Parameters | | | Solid Solubility (at.%) | | Chemical Analysis (ave wt%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| wt. % | at. % | a (nm) | c (nm) | c/a | $C_a$ | $C_c$ | $O_2$ | $N_2$ | Mg (ave. wt%) | Mg (ave. at%) |
| 0 | 0 | 0.2953 | 0.4688 | 1.587 | 0 | 0 | 0.37 | 0.075 | --- | --- |
| 5 | 9.4 | 0.2946 | 0.4728 | 1.605 | 0 | 7.6 | 0.673 | 0.095 | 5.4 | 10.11 |
| 10 | 17.9 | 0.2940 | 0.4755 | 1.617 | 0 | 12.7 | 0.849 | 0.119 | 9.2 | 16.6 |
| 15 | 25.8 | 0.2956 | 0.4757 | 1.609 | 1.2 | 13.0 | 0.919 | 0.219 | 11.1 | 19.8 |
| 20 | 33.0 | 0.2953 | 0.4761 | 1.612 | 0 | 13.8 | 1.152 | 0.202 | 15.9 | 27.2 |
| 25 | 39.6 | 0.3018 | 0.4835 | 1.602 | 25.1 | 27.8 | 1.225 | 0.256 | 19.7 | 32.6 |

Table IV.  Results from experiment 2.

| Mg Content | | Lattice Parameters | | | Solid Solubility (at.%) | | Chemical Analysis (ave. wt%) | |
|---|---|---|---|---|---|---|---|---|
| wt. % | at. % | a (nm) | c (nm) | c/a | $C_a$ | $C_c$ | $O_2$ | $N_2$ |
| 5 | 9.4 | 0.2966 | 0.4750 | 1.6015 | 5.1 | 11.8 | 0.595 | 0.085 |
| 10 | 17.9 | 0.2982 | 0.4752 | 1.5936 | 11.2 | 12.1 | 0.085 | 0.097 |
| 15 | 25.8 | 0.2975 | 0.4782 | 1.6074 | 8.3 | 17.7 | 1.145 | 0.115 |
| 20 | 33.0 | 0.2991 | 0.4783 | 1.5989 | 14.8 | 17.9 | 1.33 | 0.1015 |
| 25 | 39.6 | 0.2990 | 0.4811 | 1.6089 | 14.44 | 23.3 | 1.56 | 0.196 |

Table V. Results from experiment 3, (Ti-15 wt. %, 25.8 at. % Mg)

| Conditions | | Lattice Parameters | | | Solid Solubility (at. %) | | Chemical Analysis (wt. %) | |
|---|---|---|---|---|---|---|---|---|
| | | a (nm) | c (nm) | c/a | $C_a$ | $C_c$ | $O_2$ | $N_2$ |
| Standard SPEX | Hand Tight 6.5 h | 0.2957 | 0.4653 | 1.5738 | 1.4 | 0 | 1.263 | 0.211 |
| | Wrench Tight 6 h | 0.2966 | 0.4668 | 1.5738 | 5 | 0 | 1.325 | 0.471 |
| | Wrench Tight 6 h, Labconco | 0.2991 | 0.4772 | 1.5954 | 15 | 16 | 0.376 | 0.11 |
| | Wrench Tight 6 h | 0.2981 | 0.4809 | 1.6132 | 11 | 23 | 0.775 | 0.087 |
| Modified SPEX | Hand Tight 20 h | 0.2978 | 0.4798 | 1.6112 | 9 | 21 | 1.025 | 0.074 |
| | Wrench Tight 20 h | 0.3001 | 0.4806 | 1.5977 | 7 | 23 | 1.075 | 0.086 |
| | Wrench Tight 20 h | 0.2941 | 0.469 | 1.5947 | 0 | 1 | 0.725 | 0.71 |
| | Wrench Tight 20 h, Labconco | 0.2992 | 0.4806 | 1.6063 | 15 | 22 | 0.99 | 0.25 |
| UI | Hand Tight 26.5 h | 0.2979 | 0.479 | 1.6078 | 10 | 18 | 0.885 | 0.123 |
| | Wrench Tight 20 h | 0.298 | 0.4815 | 1.6157 | 8 | 13 | 1.2 | 0.062 |
| UWA | Wrench Tight 20 h, Labconco | 0.2995 | 0.4795 | 1.601 | 16.1 | 20.3 | Not yet available | |

Table VI. Results from experiment 4, (Ti-9 wt. %, 16.3 at. % Mg)

| Conditions | | Lattice Parameters | | | Solid Solubility (at. %) | | Chemical Analysis (wt. %) | |
|---|---|---|---|---|---|---|---|---|
| | | $a$ (nm) | $c$ (nm) | $c/a$ | $C_a$ | $C_c$ | $O_2$ | $N_2$ |
| Standard SPEX | Hand Tight 6 h | 0.2951 | 0.4682 | 1.5869 | 0 | 0 | 0.845 | 0.074 |
| | Wrench Tight 6 h | 0.2978 | 0.4756 | 1.5969 | 10 | 13 | 0.9 | 0.115 |
| Modified SPEX | Hand Tight 6 h | 0.2957 | 0.4690 | 1.5864 | 2 | 1 | 0.943 | 0.128 |
| | Wrench Tight 6 h | 0.2953 | 0.4678 | 1.584 | 0 | 0 | 0.71 | 0.098 |
| UI | Hand Tight 6 h | 0.2987 | 0.4760 | 1.594 | 13 | 14 | 0.811 | 0.605 |
| | Wrench Tight 6 h | 0.2954 | 0.4685 | 1.586 | 0 | 0 | 0.74 | 0.057 |
| UWA | Wrench Tight 6 h, Labconco | 0.2975 | 0.4778 | 1.6060 | 8.5 | 17 | Results not yet available | |

Table VII.  Results from experiment 5, (Ti-15 wt. %, 25.8 at. % Mg).

| Milling Time (hr.) | Lattice Parameters | | | Solid Solubility (at.%) | | Chemical Analysis (ave. wt%) | |
|---|---|---|---|---|---|---|---|
| | a (nm) | c (nm) | c/a | $C_a$ | $C_c$ | $O_2$ | $N_2$ |
| 1 | 0.2948 | 0.4685 | 1.5893 | 0 | 0 | 1.345 | 0.0915 |
| 2 | 0.2955 | 0.4700 | 1.5908 | 0.6 | 2.3 | 1.485 | 1.05 |
| 3 | 0.2955 | 0.4694 | 1.5887 | 0.7 | 1.2 | 1.49 | 0.143 |
| 4 | 0.2957 | 0.4693 | 1.587 | 1.4 | 0.9 | 1.835 | 0.485 |
| 5 | 0.2954 | 0.4680 | 1.5842 | 0.5 | 0 | 1.885 | 0.842 |
| 6 | 0.3001 | 0.4692 | 1.5637 | 18.3 | 0.8 | 1.535 | 0.476 |
| 7 | 0.2981 | 0.4686 | 1.5722 | 10.6 | 0 | 1.99 | 0.6255 |

Table VIII.  Results from experiment 7, (Ti-9 wt. %, 16.3 at. % Mg).

| Milling Time | Lattice Parameters | | | Solid Solubility (at %) | | Chemical Analysis (ave. wt%) | |
|---|---|---|---|---|---|---|---|
| (hrs.) | a (nm) | c (nm) | c/a | $C_a$ | $C_c$ | $O_2$ | $N_2$ |
| 8 | 0.2951 | 0.4888 | 1.5888 | 0 | 0.04 | 0.7 | 0.093 |
| 9 | 0.2952 | 0.4686 | 1.5875 | 0 | 0 | 0.66 | 0.14 |
| 10 | 0.2967 | 0.4691 | 1.5812 | 5.2 | 0.5 | 0.78 | 0.235 |
| 11 | 0.2987 | 0.4833 | 1.6181 | 13.2 | 27.5 | 0.915 | 0.311 |
| 12 | 0.2946 | 0.4678 | 1.5878 | 0 | 0 | 1.14 | 0.43 |
| 13 | 0.2997 | 0.4789 | 1.5979 | 17.0 | 19.1 | 1.205 | 0.56 |
| 14 | 0.2979 | 0.4781 | 1.6048 | 10.2 | 17.6 | 1.61 | 0.875 |
| 15 | 0.2970 | 0.4735 | 1.5942 | 6.5 | 8.8 | 1.945 | 1.25 |
| 16 | 0.2971 | 0.4789 | 1.6118 | 7.0 | 19.1 | 2.405 | 1.78 |

Table IX. Summary of MA results from DRA.

| Solute Content | | Lattice Parameters | | | Solid Solubility (at.%) | |
|---|---|---|---|---|---|---|
| wt. % | at. % | a (nm) | c (nm) | c/a | $C_a$ | $C_c$ |
| 9 | 16.31 | 0.2976 | 0.4769 | 1.6028 | 8.7 | 15.4 |
| 12 | 21.2 | 0.2982 | 0.4787 | 1.6054 | 11.1 | 18.8 |
| 15 | 25.8 | 0.2988 | 0.4803 | 1.6071 | 13.7 | 21.7 |
| 15* | 25.8 | 0.2984 | 0.4808 | 1.6116 | 11.8 | 22.7 |
| 18 | 30.2 | 0.2994 | 0.4814 | 1.6079 | 15.9 | 23.9 |
| 21 | 34.4 | 0.2993 | 0.4808 | 1.6064 | 15.4 | 22.6 |
| 24 | 38.4 | 0.3006 | 0.4826 | 1.6054 | 20.5 | 26.1 |

* Ul powder milled at the DRA.

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